Radiation Belt Environmental Indicators

for the Safety of Space Assets

SafeSpace Newsletter

Issue 6, Months 31-36

Dear Reader,

This is the final issue of the SafeSpace Project Newsletter. The programme has just been completed with the sixth and final semester of the project having been very productive.

The main goal of the SafeSpace project is to design and produce a Space Safety Service, i.e., a prototype service dedicated to adverse space weather events impacting near-Earth space and threatening space-borne assets. The Space Safety Service is devoted to the prediction and early warning of solar disturbance effects on Earth-orbiting satellites through the enhancement of energetic electron flux and fluence in the outer Van Allen radiation belt. Effective mitigation of the detrimental effects of such events is possible with reliable warnings and could result in cost avoidance of several billion dollars globally per decade. The design and output of the early warning system of SafeSpace is based on the requirements of space industry partners and considers the full cause-to-effect sequence, from precursors on Sun's surface to radiation belt variability. This is achieved through the synergistic use of well-established models (CNRS solar disturbance propagation tool, KULeuven EUHFORIA CME evolution model, ONERA Neural Network tool, IASB plasmasphere model, IAP VLF waves model, ONERA Salammbô radiation belts code and NKUA EMERALD radial diffusion coefficients model) that cover different regions of the complete Sun – interplanetary space – magnetosphere chain of space weather. The coupling of these distinct and complementary models enables a holistic approach of radiation belt forecasting, incorporating the study of plasma and energy flow from the Sun to the near-Earth environment, the transfer into the magnetosphere, and the effects on cold plasma density and electromagnetic wave properties, driving radiation belt dynamics. The ultimate result of the project is to provide a sophisticated model of the electron radiation belt and a space weather service prototype of tailored radiation belt environmental indicators, which provide forecasts with lead times of 2-4 days.

The programme has accomplished its goals, establishing a prototype service and an evaluation and verification of it, having improved the knowledge and understanding of the Earth's Magnetosphere, as demonstrated by several publications, presentations, hands-on seminars, splinter sessions and a plethora of

outreach activities in the framework of the project. The SafeSpace programme has been completed leaving a substantial legacy for the Safety of Space Assets.

Best Regards,

Prof. Ioannis A. Daglis

Project Progress and Outcomes

Propagating geoeffective solar wind structures to Earth (WP2 - CNRS, KULeuven, ONERA, IAP)

Work Package 2 of SafeSpace has been completed. The first part consisted in building, testing and validating a modelling pipeline which, based on several modelling tools, allows to predict solar wind parameters at the Lagrange L1 point solely based on solar magnetograms. A second part (task 2.4) consisted in predicting geomagnetic indices based on these L1 parameters and using machine learning algorithms (neural networks). These indices serve as input to other modelling tools in Work Package 3. All interfaces have been defined, implemented and permitted to propagate and forecast solar perturbations all the way from the solar surface to near-Earth. The 1D component of the pipeline is now essentially operational.

Inner magnetosphere dynamics (WP3 – BIRA-IASB, IAP, NKUA, ONERA)

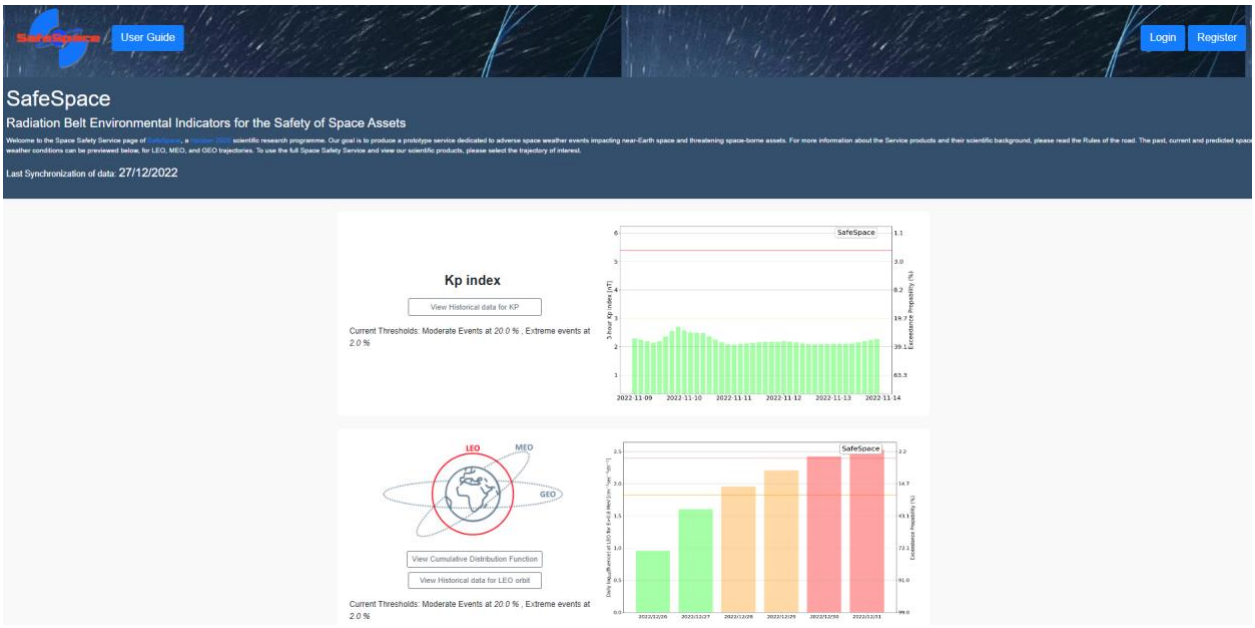
Work Package 3 of SafeSpace is now completed. It has been focused on defining a model of internal drivers for a space weather service prototype dedicated to the radiation belts, including an accurate description of the background plasma density and its variability; on updating a model of wave-particle interactions using previous and new observations, on developing a novel machine learning model for the radial diffusion coefficients and using a new background plasma density model; on improving the existing Salammbô electron radiation belt model according to new definition of interplanetary as well as magnetospheric drivers; on producing high fidelity past history of radiation belt dynamics and therefore a realistic initial state for more accurate predictions; on verifying the stability of assimilation tool and Salammbô code and their convergence for various solar wind conditions for future use in prototyping activities. The latest work on the tasks of work package 3 has resulted in a successful publication of a paper on "Efficient computation of

wave-particle interactions for a dynamic description of the electron radiation belt diffusion" by N. Dahmen et al. to Journal of Geophysical Research: Space Physics. Another paper on "Improving the electron radiation belt nowcast and forecast using the SafeSpace data assimilation modelling pipeline" by A. Brunet et al. has been recently submitted for publication.

Reference: Dahmen, N., Sicard, A., Brunet, A., Santolik, O., Pierrard, V., Botek, E., et al. (2022). FARWEST: Efficient computation of wave-particle interactions for a dynamic description of the electron radiation belt diffusion. Journal of Geophysical Research: Space Physics, 127, e2022JA030518. https://doi.org/10.1029/2022JA030518

Space Safety Service (WP4 - ONERA, TAS-E, CNRS, SPARC, NKUA, IAP, IASB)

This work package is devoted to the definition and to the settings of the Safe Space service. It focuses on energetic electrons of the radiation belts, which potentially lead to internal spacecraft charging events. In a first step, user needs were collected and expressed by one major European space industry, Thales Alenia Space. Next any data/software produced or improved throughout the project were traced and the data management plan collected all the corresponding details. A final review of the data management plan (DMP) has been performed to make sure it is fully in-line with our practices. A final version was then delivered. A third sub-work package was devoted to the chaining of all the tools involved in the prototyping activity (from the outputs of WP2 to the energetic electron phase space density production). Then, radiation belt activity indices were derived and are made available to any end-user on a dedicated web site. Finally, from those results, support web pages are dedicated to the Galileo constellation, which is located in the heart of the electron belt.



Evaluation and Verification (WP5 - TAS-E, SPARC, KU LEUVEN)

This work package is devoted to the evaluation and verification of the SafeSpace Safety service. The main objective of the WP5 is to set the characterization of functionality, adequacy to user needs and limitations in order to effectively warn end users and also to identify any appropriate improvements.

Main tasks include the definition of an appropriate evaluation method of the service, the evaluation of the SafeSpace main tool and the verification of its accuracy, the evaluation of the final products and support services which are dedicated to Galileo satellites and also the simulation and evaluation of a mission with SafeSpace forecasting data at Lagrange 5.

The first part of this work package is the definition of evaluation method (WP5.1) which consists on the definition of an appropriate evaluation method to validate the SafeSpace service. The evaluation method is based on a comparison of the SafeSpace service provided data against similar data coming from different existing tools like the ones provided by NOAA and ESA. Since the analysis of forecast data without understanding historical data is a challenging task, these historical data coming from similar existing tools will be used to validate SafeSpace services by correlating past weather events with past anomalies and service outages. The main idea of the evaluation method follows the concept of a three – stage approach for past, real-time and forecast data.

The second part of this work package is the validation report of the SafeSpace service (WP5.2) which contains the evaluation and verification of the SafeSpace service according with the validation plan written on WP5.1. Firstly, it is analyzed the SafeSpace service web visual aspect and information available, then it is reported which space weather data SafeSpace service is providing and which space operators would like to have on SafeSpace web. Then, the analysis of data is divided in three parts: past, where historical data of electron flux for energies higher than 0,8 MeV from GOES15 is compared against data used for building SafeSpace service, present, where Kp index of SafeSpace is compared with the same provided by ESA at its Space Weather Portal, and future, where forecast of SafeSpace of daily electron flux (for energies higher than 0,8 MeV for GEO) predicted values are compared with the real ones. Finally, all these validation test of data are summarized in indexed tables and comparison results are shown in plots.

Exploitation, dissemination, and communication (WP6 - NKUA, ONERA, KU LEUVEN, IAP, BIRA-IASB, TAS-E, CNRS, SPARC)

This Work Package is devoted to the exploitation and dissemination of results to the scientific community, the space industry and spacecraft operators, and furthermore the deployment of a range of communication tools, techniques and activities appropriate for different public audiences.

Web presence

As always, you may find this newsletter along with several information regarding project details, description, goals, participants, news and additional useful facts on our user-friendly [SafeSpace website], which now has a link for the service and is regularly updated with new information.

Scientific dissemination of results

The past six months have been very productive publication-wise. SafeSpace peer-reviewed publications are provided on the [project website.] Oral and poster presentations from international conferences during the last 6 months may be found on the website as well.

The SafeSpace team has disseminated the Project results in scientific publications, as well as through presentations in Conferences and Workshops. Since the start of the Programme, there have been **15 Publications** in open access scientific journals, and **43 Oral and Poster Presentations** in Conferences, Seminars and Workshops worldwide. Additionally, **3 Topical Discussion & Splinter Meetings** have been organized, as well as **2 Dedicated Workshops** by the SafeSpace Team. You can view all available material below.

Scientific Publications

2022 JGR Space Physics

FARWEST: Efficient Computation of Wave-Particle Interactions for a Dynamic Description of the Electron Radiation Belt Diffusion

Nour Dahmen, Angélica Sicard, Antoine Brunet, Ondrej Santolik, Viviane Pierrard, Edith Botek, Fabien Darrouzet and Christos Katsavrias (2022). FARWEST: Efficient Computation of Wave-Particle Interactions for a Dynamic Description of the Electron Radiation Belt Diffusion. *Journal of Geophysical Research: Space Physics*, 127, e2022JA030518.
https://doi.org/10.1029/2022JA030518 – View Published PDF

frontiers in Astronomy and Space Sciences

An event of extreme relativistic and ultra-relativistic electron enhancements following the arrival of consecutive corotating interaction regions: Coordinated observations by Van Allen Probes, Arase, THEMIS and Galileo satellites

Afroditi Nasi, Christos Katsavrias, wwwIoannis A. Daglis, Ingmar Sandberg, Sigiava Aminalragia-Giamini, Wen Li, Yoshizumi Miyoshi, Hugh Evans, Takefumi Mitani, Ayako Matsuoka, Iku Shinohara, Takeshi Takashima, Tomoaki Hori and Georgios Balasis (2022). An event of extreme relativistic and ultra-relativistic electron enhancements following the arrival of consecutive corotating interaction regions: Coordinated observations by Van Allen Probes, Arase, THEMIS and Galileo satellites. *Frontiers in Astronomy and Space Sciences*, 9:949788, 2022.
https://doi.org/10.3389/fspas.2022.949788 – View Published PDF

Annales Geophysicae

The "SafeSpace" database of ULF power spectral density and radial diffusion coefficients: dependencies and application to simulations

Christos Katsavrias, Afroditi Nasi, Ioannis A. Daglis, Sigiava Aminalragia-Giamini, Nourallah Dahmen,

Oral Presentations

2022

Advanced Prediction of the Outer Van Allen Belt Dynamics and a Prototype Service: the H2020 SafeSpace project

Daglis, I. A. and the SafeSpace Team: Advanced Prediction of the Outer Van Allen Belt Dynamics and a Prototype Service: the H2020 SafeSpace project , EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-6518, https://doi.org/10.5194/egusphere-egu22-6518, 2022.

Radial diffusion coefficients database in the framework of the SafeSpace project: A Machine Learning model and the application to radiation belt simulations

Daglis, I. A., Katsavrias, C., Aminalragia-Giamini, S., Nasi, A., Dahmen, N., Brunet, A., Bourdarie, S., and Papadimitriou, C.: Radial diffusion coefficients database in the framework of the SafeSpace project: A Machine Learning model and the application to radiation belt simulations, EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-6555, https://doi.org/10.5194/egusphere-egu22-6555, 2022.

On the Generation of Pi2 Pulsations due to Plasma Flow Patterns Around Magnetosheath Jets

Katsavrias, C., Raptis, S., Daglis, I., Karlsson, T., Georgiou, M., and Balasis, G.: On the Generation of Pi2 Pulsations due to Plasma Flow Patterns Around Magnetosheath Jets, EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-5502, https://doi.org/10.5194/egusphere-egu22-5502, 2022.

Radiation belt model including semi-annual variation and Solar driving (SENTINEL)

Aminalragia-Giamini, S., Katsavrias, C., Papadimitriou, C., Daglis, I., Sandberg, I., and Jiggens, P.: Radiation belt model including semi-annual variation and Solar driving (SENTINEL), EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-9577, https://doi.org/10.5194/egusphere-egu22-9577, 2022.

Coordinated observations of relativistic electron enhancements following the arrival of consecutive Corotating Interaction Regions

Nasi, A., Daglis, I. A., Katsavrias, C., Sandberg, I., Li, W., Allison, H., Miyoshi, Y., Imajo, S., Mitani, T., Hori, T., Shprits, Y., Kasahara, S., Yokota, S., Keika, K., Shinohara, I., Matsuoka, A., and Kasahara, Y.: Coordinated observations of relativistic electron enhancements following the arrival of consecutive Corotating Interaction Regions, EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-536, https://doi.org/10.5194/egusphere-egu22-536, 2022.

SafeSpace: Making Space a Safer place for Europe's assets

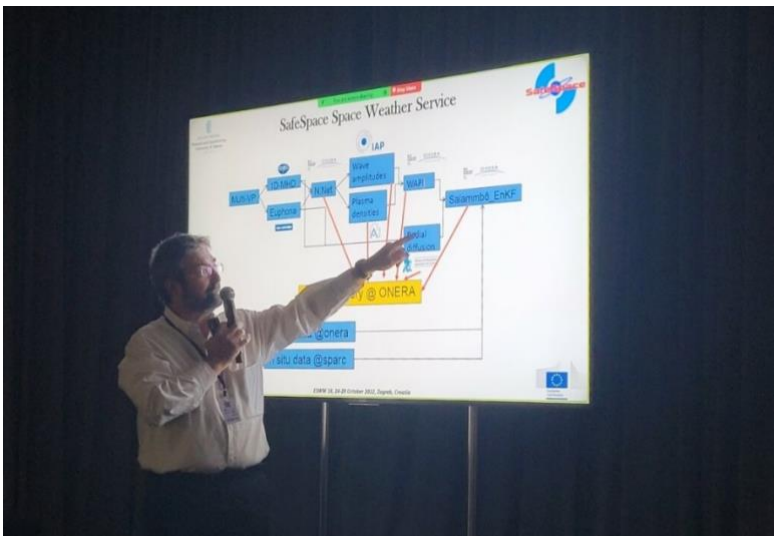
On Thursday, March 31st, 2022, Prof. Ioannis Daglis, participated in the Workshop "EU-funded R&I for Space Sciences" of DG Defense Industry and Space (DEFIS) of the European Commission, with a presentation on "SafeSpace: Making Space a Safer place for Europe's assets".

Organisation of dedicated splinter sessions and of a targeted workshop

The 5th Project Board Meeting and the 26th Technical Commitee Meeting of SafeSpace were both held at the Museum of the NKUA, in Plaka, Athens, Greece, on July 14th and 15th, 2022. The agenda included a talk titled "The extreme solar and geomagnetic storms in January 1938" by Dr. Hishashi Hayakawa.

A Hands-on Users Workshop was also held on Tuesday, 27 September 2022, on the premises of the Hellenic Space Center in Athens. The Workshop was targeted to our Advisory Panel Members as well as other Users and Stakeholders, and was dedicated to the presentation of the SafeSpace service and to discussions on its functionality, content and format.

A dedicated Topical Discussion Meeting titled "The Prototype SafeSpace Space Weather Service" was held at the European Space Weather Week (ESWW) 2022 (24–28 October 2022). The Topical Discussion Meeting was dedicated to our prototype space weather service, in the scope of the ESWW 2022 conference in Zagreb, Croatia. Prof. Ioannis Daglis, Dr. Sebastien Bourdarie, and Dr. Christos Katsavrias chaired the meeting. A presentation about the project and the service was given to both on site and online participants, who engaged in a fruitful discussion.

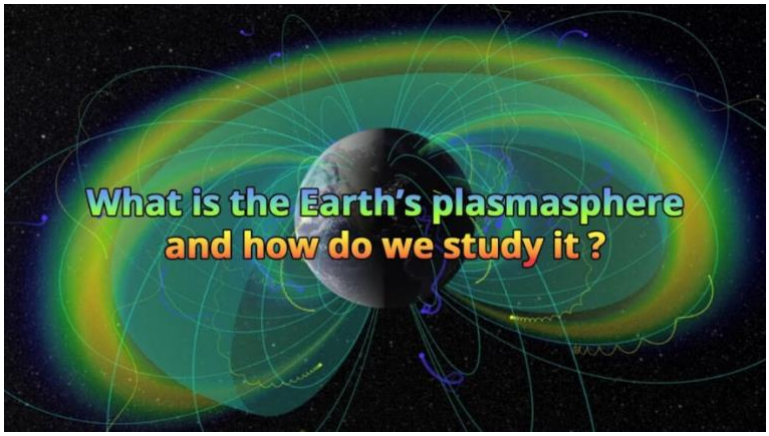


Public engagement

The team has been recovering from the Covid-19 pandemic and is slowly adapting to the new border conditions imposed by the pandemic. The outreach plan has been adapted to the intra-pandemic reality and the public engagement activities have vigorously been resumed.

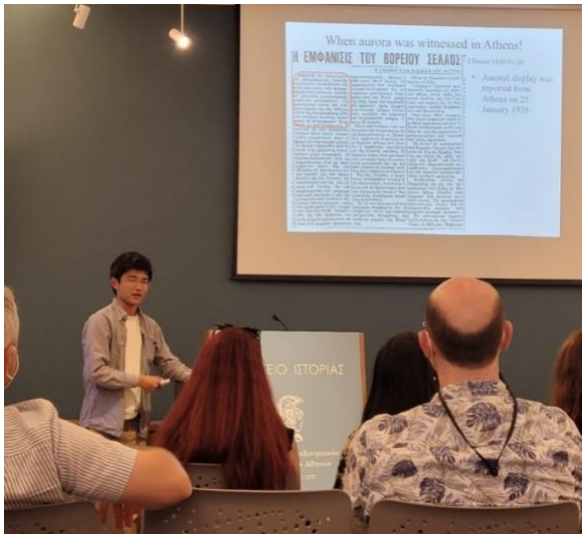
Six face-to-face public outreach activities were organized during the past semester, in Athens and in Prague, an on-line lecture was given and an educational video has been released.

An educational video about plasmasphere was created by BIRA-IASB. The plasmasphere is a region of space around Earth where electrically charged particles are trapped by the Earth's magnetic field. This little-known part of our planet's magnetosphere has very interesting properties, and changes in the plasmasphere can have important consequences for life on the surface. In this video, three scientists of the Royal Belgian Institute for Space Aeronomy explain in further detail what the term "plasmasphere" means, how they study it and why.



Dr. Sébastien Bourdarie, researcher at Office National d'Etudes et de Recherches Aérospatiales (ONERA, France) and ONERA SafeSpace Team Leader, gave a public outreach talk titled "Space Weather Impacts on Spacecraft". The talk was about space weather impacts on spacecraft, and was given in the gardens of the Visitor Center of National Observatory of Athens located on the Hill of the Nymphs, in Athens, Greece.

On the same premises took place the second public outreach talk titled "Historical Auroral Displays and Millennial Space Weather History" that was given by Dr. Hishashi Hayawawa (Designated assistant professor, Institute for Advanced Research, Nagoya University, Japan). This talk visualized recent archival investigations for such historical auroral records from the early modern observations to the ancient period. Special emphases are placed on some cases with Greek observations too. These investigations allow us to extend our space-weather chronology for three millennia and access a number of extreme storms in this interval.

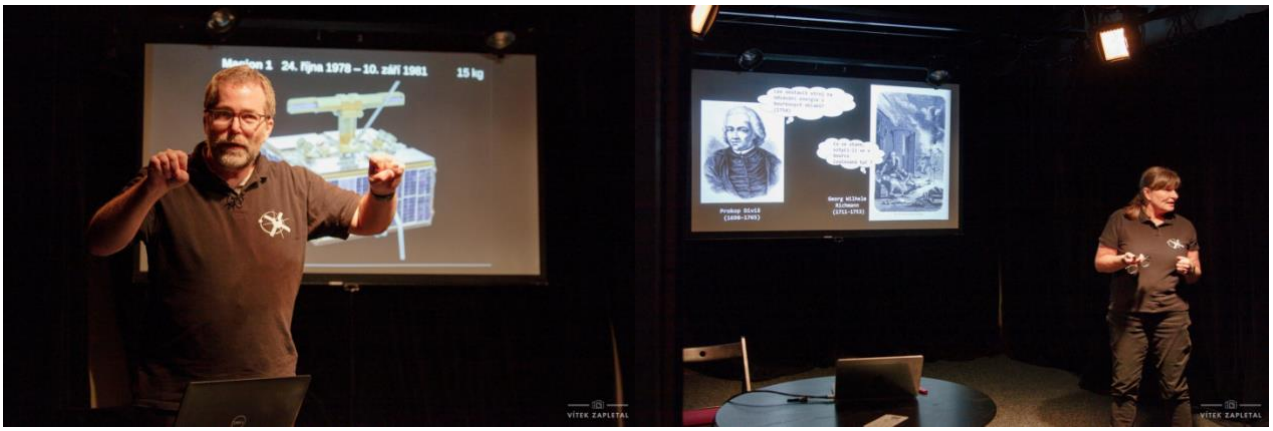


SafeSpace participated in the Open days "Space for climate", Brussels, with the educational plasmasphere video, created by BIRA-IASB. Open Days "Space for climate" has been a weekend of fun and games for the youngest, scientific discovery for the whole family and direct interaction with the scientists themselves.

Visitors who stepped onto the grounds of the Space Pole in Uccle, had the opportunity to learn about plasmasphere. The plasmasphere is a region of space around Earth where electrically charged particles are trapped by the Earth's magnetic field. This little known part of our planet's magnetosphere has very interesting properties, and changes in the plasmasphere can have important consequences for our life on the surface.

SafeSpace participated in Researchers' Night Greece, with an exhibition titled "Geomagnetic storms and satellite hazards", including the presentation of a scientific magnetometer, the sounds of space, and a mock up of the terrestrial magnetosphere. The activity was hosted in Athens by the National Technical University of Athens.

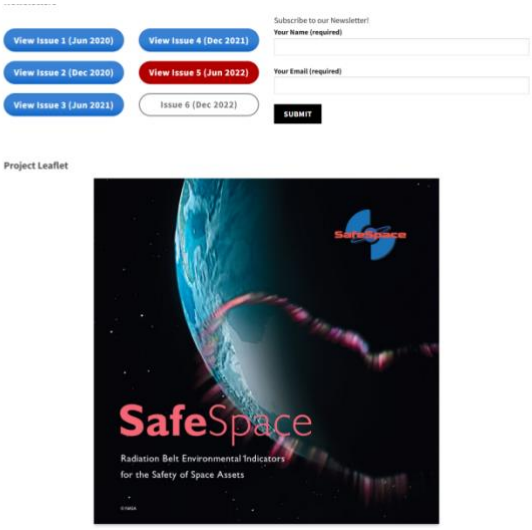
SafeSpace participated in Researchers' Night Prague, with several activities. Ivana Kolmasova and Ondrej Santolik gave public talks titled "Journey for lightning in the solar system" and "Music of the spheres", respectively. Additionally, two exhibitions were held, with sounds of space (a big TV screen with interactive on demand sounds and explanation), and the Planeterella, where David Pisa demonstrated the interaction of the solar wind with the Earth's magnetic field.



Moreover, SafeSpace participated in Athens Science Festival (ASF), on October 21-23, 2022 at Technopolis City of Athens. The activity, "Space Weather & Earth's Magnetic Field" was presented in the Interactive Exhibition section of the ASF. In the scope of the SafeSpace activity, a scientific magnetometer was exhibited, an instrument used to take measurements of the terrestrial magnetic field. Its fluctuations are affected by space weather phenomena, which can affect life on Earth (communications, navigation, power networks etc). Additionally, the relation between science and art was highlighted, through the "sounds of space" that are unveiled by a magnetometer.

Finally, Konstantina Moutsouroufi, WP6.5 Task Leader, gave an online lecture for the students of Panormos General Lyceum, Rethymnon, Crete, Greece, via The Tipping Point platform. The discussion was about different aspects of Astrophysics and research related to space.

Alla SafeSpace Electronic Newsletter issues remain available on the project's website along with the SafeSpace Leaflet. It has been a pleasure communicating Space Safety to all our audiences!



SAFESPACE

"Radiation Belt Environmental Indicators for the Safety of Space Assets"

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